

# Particle Dark Matter

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## 1 Introduction: Three Arguments for Non-baryonic Dark Matter

Several lines of evidence suggest that some of the dark matter may be non-baryonic: the non-detection of various plausible baryonic candidates for dark matter inferred, e.g., from galaxy rotation curves and from cluster of galaxy velocity dispersions, the need for non-baryonic dark matter for theoretical models of galaxy formation, and the large discrepancy between dynamical measurements implying  $\Omega_0 > 0.2$  and the baryon abundance inferred from big bang nucleosynthesis,  $\Omega_b h^2 = 0.015$ . There are a number of well-motivated dark matter candidates: massive neutrinos, supersymmetric dark matter and “invisible” axions. Many of these dark matter candidates are potentially detectable by the current generation of dark matter experiments.

## 2 The Case For Non-Baryonic Matter

While there is a consensus in the astronomical community that most of the mass of our Galaxy and of most galaxies is in the form of some non-luminous matter [70], there is only speculation about its nature.

In his lecture, Charles Alcock (see the contribution by C. Alcock to these proceedings) presents a report of recent progress in efforts to detect baryonic dark matter. Here, I will focus on non-baryonic dark matter.

I will begin by presenting three arguments that suggest that the dark matter is non-baryonic. None of these arguments are definitive. John Bahcall has urged the speakers to identify interesting problems for graduate students.

In addition to the grand challenge of detecting the dark matter, I believe that an easier problem is to make some of the arguments for dark matter more compelling.

## 2.1 We've looked for baryonic dark matter and failed

Astronomers have already eliminated a number of plausible candidates for the dark matter. X-ray observations of galaxies imply that only a small fraction of the mass of a typical galaxy is in the form of hot gas [6, 44]. Even in rich clusters, hot gas makes up less than 20% of the total mass of the system [14]. Neutral hydrogen gas is detectable through its 21 centimeter emission: in most galaxies, neutral gas comprises only 1% of the mass of the system [56] and in only a handful of dwarf galaxies does the neutral gas mass exceed the stellar mass. Even in these systems (e.g., DDO 240 [17]), neutral gas does not account for more than 20% of the system mass. Molecular gas is detectable through dipole emission of CO and other non-homopolar molecules: in most galaxies, the molecular gas mass appears to be less than the neutral gas mass. Low luminosity (low mass) stars, M dwarfs, have often been proposed as a dark matter candidate but HST observations show that faint red stars contribute less than 6% of the unseen matter in the galactic halo [7].

If the dark matter is composed of baryons, then these baryons must be clumped into dense bound objects to evade detection. Gerhard and Silk [29] have proposed that the dark matter consists mostly of very dense tiny clouds of molecular gas. Their model, while provocative, is only marginally consistent with current observational limits. A more widely accepted proposal is that the dark matter consists of very low mass stars, called brown dwarfs. These brown dwarfs are not massive enough to burn hydrogen, so that their only energy source is gravitational energy.

While these brown dwarfs are difficult to detect through their own emission, they are potentially detectable through the gravitational effects. Paczynski [45] proposed gravitational lensing searches for these objects. Several groups have begun searching for these events in an effort to probe the nature of the dark matter.

So far, MACHO searches are not finding as many events as predicted by spherical halo models [3]; however, they can not yet rule out MACHOs as the dominant component of the halo. The current experiment is limited by both small number statistics and by uncertainties in galactic parameters. Many important galactic parameters such as the circular speed, disk scale length and the local surface density are still quite uncertain. Because of these uncertainties, the local halo density is not certain to a factor of two.

It is particularly important to accurately determine the local circular speed as our estimates of the local dark matter density is very sensitive to

its value:

$$\frac{\partial \log \rho_{\text{halo}}}{\partial \log v_c} = 2 \frac{v_{\text{tot}}^2}{v_{\text{tot}}^2 - v_{\text{disk}}^2} \sim 4 .$$

(Deriving this formula is a good exercise for a student new to dynamics. For an excellent introduction to the subject, see Binney & Tremaine [12]). Thus, a 10% uncertainty in local circular speed translates into a 40% uncertainty in the local dark matter density. Without more accurate determinations of  $v_c$ , it is difficult to definitively argue that MACHOs can not comprise much, if not all, of the mass of the dark halo.

There is also a need for better models of the LMC and more accurate measurements of its properties. Some of the lensing events reported by the MACHO and EROS collaborations may be due to "self-lensing" by the LMC [55] rather than dark matter in the halo.

## 2.2 We can't seem to make large scale structure without WIMPs

All of the most successful models for forming large scale structure assume that most of the universe is composed of cold dark matter.

Models in which the primordial fluctuations are adiabatic and the universe is comprised only of baryons and photons are ruled out by CBR observations. The predicted level of fluctuations in these models exceed the observed level by more than an order of magnitude. Isocurvature models [47] fare better; however, these models also appear to be in conflict with CBR observations [18].

The current "best fit" models have  $\Omega_0 \simeq 0.3$ ,  $H_0 \simeq 0.75$ ,  $\Omega_b \simeq 0.03$  and either a cosmological constant or space curvature (see Steinhardt's talk in these proceedings for a review). These models fit COBE observations; are consistent with age and  $H_0$  determinations; are consistent with LSS power spectrum, and are consistent with most large scale velocity measurements. While they are in conflict with the large velocities detected by Lauer & Postman [40], these large velocities are controversial [53]. Numerical simulations suggest that these models also agree with the properties of rich clusters [8].

Despite the success of structure formation models that assume non-baryonic dark matter, no one has proven a "no-go" theorem that rules out baryon-only models. It is an interesting challenge to determine what observations are needed to rule out these models.

## 2.3 Dynamical Mass is Much Larger than Big Bang Nucleosynthesis Allows

Measurements of the mass-to-light ratios in clusters suggest that  $\Omega_{\text{tot}}$ , the ratio of the total density of the universe to the critical density, exceeds 0.2 [9]. This determination of  $\Omega_{\text{tot}}$  is consistent with measurements based upon the large-scale velocity fields and the dynamics of the large-scale structure [67]. Values of  $\Omega$  less than 0.2 are very difficult to reconcile with the 500 km/s random velocities seen in large scale structure surveys and even harder to reconcile with large-scale streaming motions.

The observed (presumed cosmological) abundances of deuterium, helium and lithium are only consistent with standard big bang nucleosynthesis if the baryon density is much less than  $\Omega_{\text{tot}}$ . The best fit value for  $\Omega_b h^2 \simeq 0.015$ , which is nearly an order of magnitude below the dynamical values [72]. For example, if  $H_0 = 75$  km/s/Mpc,  $\Omega_b = 0.2$  implies that  $Y$ , the Helium/Hydrogen abundance ratio, is 0.262 and  $D/H$ , the Deuterium/Hydrogen abundance ratio, is  $10^{-6}$  [72] while if  $H_0 = 50$  km/s/Mpc,  $\Omega_b = 0.2$  implies  $Y = 0.253$  and  $D/H = 5 \times 10^{-6}$ . There are many extragalactic HII regions with  $Y < 0.25$  and best estimates imply  $Y \simeq 0.24$ . These observations appear to require either a significant modification of our ideas about big bang nucleosynthesis or the existence of copious amounts of non-baryonic dark matter. (See, however, Goldwirth & Sasselov [30] for a dissenting view).

All of the proposed modifications of BBN appear to violate known observational constraints. For example, Gnedin & Ostriker [32] proposed that an early gamma-ray background photodissociated some of the primordial Helium. This model predicts a spectral distortion of  $y > 7 \times 10^{-5}$  and a fully ionized universe.  $y$  describes the deviation of the observed spectrum from the thermal spectrum and is a measure of the energy injection in the early universe. COBE [42] found that the observed spectrum was consistent (within the experimental errors) with a thermal spectrum and constrained  $y < 2.5 \times 10^{-5}$ .

Inhomogeneous nucleosynthesis models have been studied extensively in the past few years. However, Thomas et al. [68] found that even models with large inhomogeneities imply  $Y > 0.25$  for  $\Omega_b h^2 > 0.05$ . Thus, they are also not consistent with  $\Omega_b = \Omega_{\text{tot}} = 0.2$ .

While the theory of big bang nucleosynthesis is well developed, there is still uncertainty in converting the observed line ratios to abundances. Most of the abundances for external systems assume a spherical clouds with constant rates of ionization. It would be interesting to study a nearby system such as the Orion nebula and estimate the error associated with this approximation in the analysis. Goldwirth & Sasselov [30] have made an important first step in studying the sensitivity of these element abundances to model uncertainties. There is a need for more work.

While none of these three arguments is incontrovertible, they all do suggest that most of the universe is in non-baryonic matter. The rest of this paper will review the most popular proposed candidates for non-baryonic dark matter and consider various schemes for detecting its presence.

### 3 Neutrinos as Dark Matter

In the standard big bang model, copious numbers of neutrinos were produced in the early universe. The universe today is thought to be filled with 1.7 K thermal neutrino radiation, the neutrino complement to the thermal radiation background. If these neutrinos are massive, then they can make a significant contribution to the total energy density of the universe:

$$\Omega_\nu h^2 \simeq \left( \frac{m_\nu}{100\text{eV}} \right) \quad (1)$$

Recent results from solar neutrino experiments have revived interest in neutrinos as dark matter candidates. As John Bahcall has described in his talk (see these proceedings), recent experiments appear to be consistent with the MSW solution to the solar neutrino deficit. The MSW solution implies that the difference in mass squared between the electron neutrino and another neutrino family is of order  $10^{-5} \text{ eV}^2$ . While this mass difference is much smaller than the mass needed for neutrinos to be the dark matter, it does suggest that neutrinos are massive. It is thus certainly possible that the MSW effect is due to oscillations between electron and mu neutrinos and that the tau neutrino is much more massive and comprises much of the dark matter.

There are several astronomical problems for neutrino dark matter models. Because cosmic background neutrinos have a Fermi-Dirac distribution, they have a maximum phase-space density, which implies a maximum space density [69]. Dwarf irregular galaxies [17] have very high dark matter densities and dwarf spheroidals [28] have even higher dark matter densities: neutrinos can not be the dark matter in these systems. So, if neutrinos are the dark matter in our Galaxy, then there is a need for a second type of dark matter for low mass galaxies [28]. Neutrino plus baryon models have a difficult time forming galaxies early enough and these models predict galaxy clustering properties significantly different from those observed in our universe.

There are, however, several modified neutrino models that appear more attractive. Cosmological models in which cosmic string seed fluctuations in the hot dark matter have several promising features for structure formation [2]. Mixed dark matter models in which neutrinos comprise 20% of the dark matter and the rest of the dark matter is comprised of cold dark matter also appear to be consistent with a number of observations of large scale structure [51].

### 3.1 Detecting Massive Neutrinos

While it is very difficult to detect the cosmic background of neutrinos directly, there are several experimental approaches that might be able to measure the mass of the neutrino. As I noted earlier, the detection of a stable several eV neutrino would imply that neutrinos comprise a significant fraction of the mass of the universe.

The classical approach to measuring neutrino mass are measurements of the  $\beta$  decay endpoint. Current limits from these experiments imply that the electron neutrino is not the predominant component of the dark matter; however, these experiments cannot place astrophysically interesting constraints on the mass of the mu or tau neutrino.

If the neutrino is a Majorana particle, then it might be indirectly detected through the detection of a neutrinoless double beta decay. Deep underground experiments looking for rare decays have placed very interesting limits [34] on the electron neutrino mass:  $m_{\nu_e} < 0.68$  eV. This is a limit on massive neutrinos *if* the most massive eigenstate contains a significant fraction of the electron flavor eigenstate and does not apply to all neutrino models.

Neutrino oscillation experiments are sensitive to mass differences, usually  $\Delta m^2 = m_{\nu_\mu}^2 - m_{\nu_e}^2$  and sometime  $m_{\nu_\tau}^2 - m_{\nu_e}^2$ . Recent results from the Los Alamos experiment [5], which suggest a detection of neutrino oscillations, are controversial [35].

There is a possibility of an astronomical detection of neutrino mass using neutrinos from a supernova explosion. If the neutrinos are massive, then more-energetic neutrinos arrive earlier than less-energetic neutrinos. Thus, neutrino detectors would first see higher energy events and then see less energetic events. This effect was not observed in SN 1987A, which suggests that  $m_{\nu_e} < 15$  eV [64]. Observations of a galactic supernova by Sudbury detector, which is sensitive to  $\nu_\mu, \nu_\tau$  could place interesting limits on their masses and possibly rule out neutrinos as cosmologically interesting.

## 4 WIMPs

There is broad class of particle physics candidates for the dark matter that are referred to as Weakly Interacting Massive Particles or WIMPs. This class includes several proposed particles (massive Dirac neutrinos, cosmions, SUSY relics) that have masses of order a few GeV to a few hundred GeV and interact through the exchange of W's, Z's, higgs bosons and other intermediaries. In this talk, I will give a brief introduction to WIMPs. I refer interested readers to recent, more detailed reviews [61, 50, 37].

The early universe is a wonderful particle accelerator. WIMPs could be produced through reactions such as  $e^+ e^- \rightarrow X \bar{X}$ , where  $X$  denotes the

WIMP particle. WIMPs, of course, can be annihilated through the backreaction,  $X\bar{X} \rightarrow e^+ e^-$ . As long as  $T > m_X$ , the WIMP number density would be comparable to the number density of electrons, positrons, and photons. However, once the temperature drops below  $m_X$ , the WIMP abundance begins to drop. It will fall until the WIMP number density is so low that the WIMP mean free time for annihilation exceeds the age of the universe. This “freeze-out” occurs at a density determined by the WIMP annihilation cross-section and implies that

$$\Omega_x h^2 \simeq \left( \frac{\sigma_{\text{ann}}}{10^{-37} \text{cm}^2} \right)^{-1}$$

The first proposed WIMP candidates were heavy fourth generation neutrinos [36, 41]. If the neutrino mass was of order 2 GeV, then its relic abundance would be sufficient for  $\Omega_\nu = 1$ . Experimental dark matter searches [1] ruled out these particles as dark matter candidates.

Supersymmetry is an elegant extension of the standard model of particle physics. It is the only so-far “unused” symmetry of the Poincare group and has the virtue of protecting the weak scale against radiative corrections from GUT and Planck scale. Local supersymmetry appears to be an attractive route towards unifying all four forces and is a basic ingredient in superstring theory. Supersymmetry transforms bosons into fermions (and vice-versa). As supersymmetry has a new symmetry, R parity, it can imply the existence of a new stable particle. In much of the parameter space of the minimal supersymmetric model, this new stable particle (which we will refer to as the “neutralino”) has predicted properties such that it would comprise much of the density of the universe [25].

## 4.1 Searching for WIMPs

While WIMPs interact weakly, they are potentially detectable [31, 73, 37]. The flux of WIMPs through an experiment is quite large:  $10^6 \text{ (m/GeV)}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ . The difficulty lies in detecting the rare WIMP interactions with ordinary matter.

The challenge for dark matter experimenters is to design an experiment that is simultaneously sensitive to few keV energy depositions and has a large mass (many kilograms) of detector material. The experiment must also have superb background rejection as the expected event rate, less than an event/kilogram/day, is far below most backgrounds. There are two potentially experimental signatures that can aid in the WIMP search: a roughly 10% annual modulation of the event rate due to the Earth’s motion around the Sun [24] and a large ( $\sim 50\%$ ) asymmetry in the direction of the WIMP flux due to the Sun’s motion through the galactic halo [63].

The first generation of WIMP experiments were rare-event experiments that were adapted to search for dark matter. The first set of experiments were ultra-low background germanium semiconductor experiments [1, 16, 54] that were developed as double beta-decay experiments and modified into dark matter detectors. In these experiments, a recoiling Ge nucleus produces  $e^-$ -hole pairs that are detectable down to recoil energies  $\sim 5$  keV. These experiments have been limited by microphonics, electronic noise, and by cosmogenic radioactivity.

We are now entering the era of second generation experiments that have been designed primarily as dark matter detectors. In this section, I will highlight several of the promising experimental technologies.

The Heidelberg-Moscow germanium experiment is a modification of the early germanium experiments. It consists of 6 kilogram of purified  $^{76}\text{Ge}$  detector in Gran Sasso Tunnel. Since it does not contain  $^{68}\text{Ge}$ , it has a reduced cosmogenic background. In this experiment, electronics and microphonics are the dominant background. This experiment places the best current limits on the halo density of WIMPs more massive than 50 GeV [11].

Rather than detecting the electron-hole pairs produced by recoiling nuclei, the Stanford silicon experiment [76] detected the ballistic phonons produced by recoiling silicon nuclei. This experiment has been calibrated by neutron bombardment. The Munich group is developing a silicon detector that will detect the ballistic photons with an SIS junction [48].

At Berkeley, the CfPA group is developing a detector that is sensitive to both phonon and electron-hole pairs. This dual detection allows much better background rejection as electrons excited by radioactive decays have a different photon and electron-hole pair signature than nuclear recoils. Neutron bombardment experiments suggest that this dual detection technique can reject  $\sim 99\%$  of radioactive background [58]. A more massive experiment that utilizes this technique has the potential to probe into interesting region of parameter space in supersymmetric theories.

Several groups are developing scintillators that are potential WIMP detectors. There are several scintillator experiments currently under development: a 36.5 kg NaI experiment in Osaka that has begun to place interesting limits on heavy neutrinos [27, 26]; the Rome/Beijing/Saclay experiment [13], a smaller detector, with sensitivities similar to the Osaka experiment; and a Munich sapphire scintillator experiment that is designed to be sensitive to low mass ( $m < 10$  GeV) WIMPs. This technology has several advantages over the germanium and silicon semiconductors; the material is sensitive to spin-dependent coupling (although, this is now thought to be less important for supersymmetric dark matter detection [37]) and it is relatively easy to build very large mass detectors. The challenge for these experiments is to improve their background rejection. Spooner & Smith [65] suggest that it might be possible to have some rejection of radioactive  $\gamma$ 's in these NaI scintillators through measurements of UV and VIS signatures of recoils [65].



#### 4.1.1 Gas Detectors

Time-Projection Chamber (TPC) detectors have been used extensively in particle physics experiments. While a gas detector with sufficient mass to be sensitive to neutralinos would have an enormous volume, this technology does offer the possibility of detecting the direction of WIMP recoil. Due to the Earth’s motion around the Sun, the WIMP recoil events are expected to be highly asymmetric [63]. Buckland et al. [15] report their development of a 50 g H prototype detector. This detector, developed at UCSD, has been tested with neutron source and is potentially scalable to larger masses.

#### 4.1.2 Superconducting Grains

Superconducting grains have an illustrious history in dark matter detection. Drukier & Stodolsky [23] proposed superconducting grains for neutrino detectors and this work led Goodman & Witten [31] and Wasserman [73] to propose the development of WIMP detectors.

A superconducting grain detector would consist of numerous micron size superconducting grains in a meta-stable state. When one of these grains is heated by WIMP recoil, it would undergo a phase transition to the normal state. The resultant change in  $B$  field would be detected by a SQUID. Most background events, due to radioactivity, would flip multiple grains in the detector. Since the events can also be localized in the detector, this can further enhance background rejection as background events should occur primarily near the outside of the detector. The challenge for superconducting grain detector development is the production of large number of high quality grains. Recently, the Bern group [4] has been able to report significant progress in this direction: they been able to build a superconducting grain detector with several different types of grains (Sn, Al and Zn grains), which they have calibrated with a neutron source.

#### 4.1.3 “Old” Mica

WIMP detection requires exposure times of  $\sim 100$  kg-years. A novel approach is to replace the 100 kg detector with small amounts of material that has been exposed for nearly a billion years. Snowden-Ifft and collaborators [62] have looked for tracks produced by WIMP scatters off of heavy nuclei (such as cadmium) in ancient Mica. They identify these tracks by etching the Mica and have calibrated their experiment by bombarding the Mica with a neutron source.

#### 4.1.4 Atomic Detectors

Recently, Glenn Starkman and I proposed searching for inelastic collisions of SUSY relics with atoms [66]. The cross-sections for these interactions are largest for  $\delta E \sim 1$  eV. While the cross-section for atomic interactions are smaller than nuclear interactions, there is a wider range of material that could be used for detecting these atomic interactions. There are not yet any experimental schemes proposed to look for WIMP-atom scatterings. This proposal requires more experimental and theoretical study.

### 4.2 Indirect WIMP detection

The Sun can potentially serve as an enormous WIMP detector. WIMPs streaming through the galactic halo would be gravitationally focused into the Sun, where they would be captured through collisions with atoms in the Sun's center [49]. Neutralinos are their own anti-particles; thus, the neutralinos in the Sun would annihilate each other. When neutralinos annihilate, they will produce high energy neutrinos that are potentially detectable in terrestrial experiments [59]. These few GeV neutrinos are much more energetic than the MeV solar neutrinos produced through solar nucleosynthesis. There is also the possibility of detecting WIMPs in the halo through their annihilation into protons and anti-protons, into electrons and positrons and into  $\gamma$ 's. The predicted rates for these processes are unfortunately rather low [21].

There have been several experiments that have looked for WIMP annihilations in the Sun. Currently, there are limits from the Kamionkande, Frejus, and MACRO experiments. In the coming years, we can look forward to more sensitive searches by the DUMAND, AMANDA and NESTOR experiments. While these searches are worthwhile, Kamionkowski et al. [38] have argued that direct experimental searches may be a more effective technique than searches for neutrinos from annihilations of SUSY relics in the Sun. However, for the rarer models with predominantly spin interactions, the converse is most likely true. They conclude that for most of parameter space, 1 kg of direct detector is equivalent to  $10^5$ - $10^7$  m<sup>2</sup> of indirect detector.

### 4.3 What is to be Done?

Besides the challenge of helping to make any of the promising experiments discussed above work, there are a number of interesting open problems in the WIMP detection field for both theorists and experimentalists. Advances at LEP and at the Tevatron continue to place new limits on the properties of SUSY particles and may provide hints of their existence. We need an on-going reassessment of the viability of different experiment approaches (see e.g., [38]). There is still much work to be done on the interactions of neutralinos

with ordinary matter (see e.g., [66]). In particular, it would be useful to consider the excitation of atomic levels through WIMP-nuclei collisions.

Advances in technology may enable new kinds of WIMP detectors. It would be very exciting to be able to build a detectors composed large numbers ( $\sim 10^{31}$ ) spin aligned nuclei. As this detector would have directional sensitivity, it would be sensitive to the large angular asymmetry in the WIMP flux [63]. The development of new purification techniques in the semi-conductor industry may help facilitate the construction of ultra-low background Silicon and Germanium detectors. It would be very exciting if an experiment such as DUMAND or AMANDA with their large detection volumes could be redesigned so that it was sensitive to SUSY relics scattering events. Because of their large active volumes, even lower event rate processes such as inelastic scattering are of potential interest for these experiments. Close collaborations between experimentalists, theorists and technologists are need to advance the search for SUSY relics.

## 5 Axions

Axions are another well-motivated dark matter candidate. While axions are much lighter than the SUSY relics discussed in the previous section and are produced by a very different mechanism, they are indistinguishable to theoretical cosmologists studying galaxy formation and the origin of large scale structure. Both axions and SUSY relics behave as cold dark matter (CDM) and cluster effectively to form galaxies and large-scale structure. (See Steinhardt's and Ostriker's articles on structure formation).

Axions were proposed to explain the lack of CP violation in the strong interaction [74, 75]. They are associated with a new U(1) symmetry: the Peccei-Quinn symmetry [46]. As originally proposed, axions interacted strongly with matter. When experimental searches failed to detect axions, new models were proposed that evaded experimental limits and had the interesting consequence of predicting a potential dark matter candidate [39, 57, 77, 22].

In the early universe, axions can be produced through two very distinct mechanisms. At the QCD phase transition, the transition at which free quarks where bound into hadrons, a bose condensate of axions form and these very cold particles would naturally behave as cold dark matter. Axions can also be produced through the decay of strings formed at the Peccei-Quinn phase transition [19, 20]. Unless inflation occurs after the P-Q phase transition, string emission is thought the dominant mechanism for axion production. While Sikivie and collaborators [33] has argued that Davis and Shellard overestimated string axion production, recent analysis [10] confirm that strings are likely to be the dominant source of axions. Axionic strings will not produce an interesting level of density fluctuations as their predicted mass per unit length is far too small to be cosmologically interesting.

The properties of the axion are basically set by its mass,  $m_a$ , which is inversely proportional to the scale of Peccei-Quinn symmetry breaking,  $f_a$ . The smaller the axion mass, the more weakly the axion is coupled to protons and electrons. Raffelt [52] reviews the astrophysical arguments that imply  $m_a < 10^{-2}$  eV. If the axion had a larger mass, then it would have had observable effects on stellar evolution and on the dynamics of SN 1987A. If we require that the energy density in axions not “overclose” the universe, then  $\Omega_a h^2 < 1$  implies that  $m_a > 1\mu\text{eV}$ . If strings play an important role in axion production, then the cosmological limit lies closer to  $m_a > 1\text{meV}$  and there is only a narrow window for the axion model [52].

Axions are potentially detectable through their weak coupling to electromagnetism [60]. In the presence of a strong magnetic field, the axionic dark matter could resonantly decay into two photons. The first generation of detectors consisted of experiments in Florida and at BNL that looked for this decay in a tunable resonant cavity. Since the Peccei-Quinn scale is not well determined, these experiments have to scan a wide range of frequencies in their search for the axion. These experiments were an important first step towards probing an interesting region of parameter space.

In the past few years, the search for axions has been revived by two new experimental efforts. Karl von Bibber [71] and his group at LLNL have built a cryogenically cooled cavity; this detector should be able to reach into cosmologically interesting region of parameter space. In Kyoto, Matsuki [43] and his group plan to use an atomic beam of Rydberg atoms as an axion detector. This detector would detect an axion in the galactic halo through its excitation of a Rydberg atom in the  $n$ -th energy state to the  $n+1$  energy state. The Kyoto collaboration also promises to probe the cosmologically interesting region of parameter space.

## 6 Conclusions

While there is no conclusive evidence for non-baryonic dark matter, there are strong hints that it may comprise most of the mass of the universe. There are several well motivated particle physics candidates for non-baryonic dark matter. Most excitingly, these candidates are potentially detectable in experiments currently under development.

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